15. Seismic Failure of Spillway Radial Gates

Key Concepts and Factors Affecting Risk

Load Carrying Mechanism

Spillway radial gates (sometimes called tainter gates) transfer the reservoir load to the trunnion pin through compression of the relatively slender gate arms (see Figure 15-1). The primary concern is for buckling of the gate arms under the increased loading resulting from strong seismic shaking. This is not a ductile failure, and can occur suddenly.

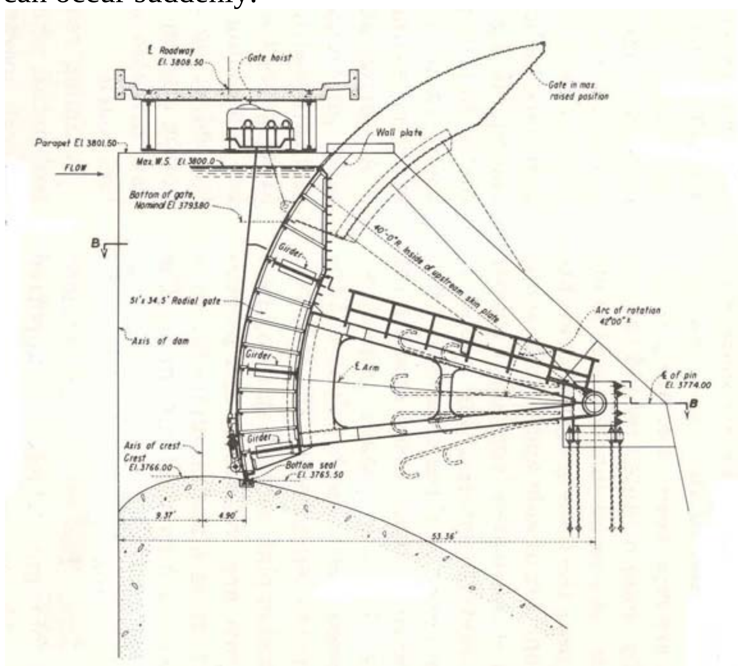


Figure 15-1 – Section through Radial Gate

Trunnion Pins and Trunnion Anchors

Equally important to carrying the load, but typically less critical in terms of capacity, are the radial gate trunnion pins and anchorage. However, these must be checked. The shear strength of the trunnion pin should be compared to the load imparted by the gate arms attached to it. The trunnion anchorage typically carries the load in tension, and its capacity should also be compared to the gate loads that it is required to carry. Trunnion anchors can be configured in a variety of ways. They can consist of steel bars or steel plates; the anchorage can be achieved by steel plates or hooks at the end of the anchors; and, the anchors can be fully bonded to the surrounding concrete or unbonded, allowing for movement of the trunnion pin in response to loading.

Size of Radial Gates
Spillway radial gates come in all sizes. Large radial gates, 50 feet or more on a side, are common. Failure of one or more gates could exceed the safe channel capacity or surprise downstream recreationists with life-threatening flows.

Reservoir Water Level
Reservoir water level on the gates is a key parameter since it affects the loading on the gates (both statically and dynamically) and also the consequences of gate failure (due to the effect on the breach outflow).

Reservoir Operations
If the reservoir level is typically at or near the top of the gates, this is a more hazardous situation than if the reservoir fluctuates significantly during the course of a year. The likelihood of various reservoir levels can typically be estimated from the historic reservoir exceedance curves.

Seismic Hazard
Most radial gates will have some reserve capacity beyond the stress levels created by full reservoir static loads. However, the level of seismic loading in combination with the reservoir level at the time of loading will determine whether the gate arms are overstressed, and if so to what level.

Number of Gates
Multiple spillway gates on a given project will typically increase the probability of a gate failure (with the outcome varying from a single gate failing to all the gates failing). Multiple spillway gate failures also create the potential for a large breach outflow and higher potential loss of life.

Maintenance of Spillway Gates
Gates that are well maintained can usually be relied upon to have their original design capacity at the time of an earthquake. If gates are not maintained and the gate members corrode, the original design capacity may be reduced. A recent examination is usually needed to determine the condition of the gates.

Event Tree

An example event tree is shown in Figure 15-2 that is relatively simple, and typical of what might be used. Each branch consists of three nodes – a seismic load range, a reservoir elevation range, and the conditional probability of gate failure given the load probabilities (with the associated consequences). If the gates are loaded to the point of overstressing the radial gate arms, the gate arms can buckle and fail, leading to gate collapse and reservoir release without additional steps in the event sequence. Refer also to the section on Event Trees for other event tree considerations.

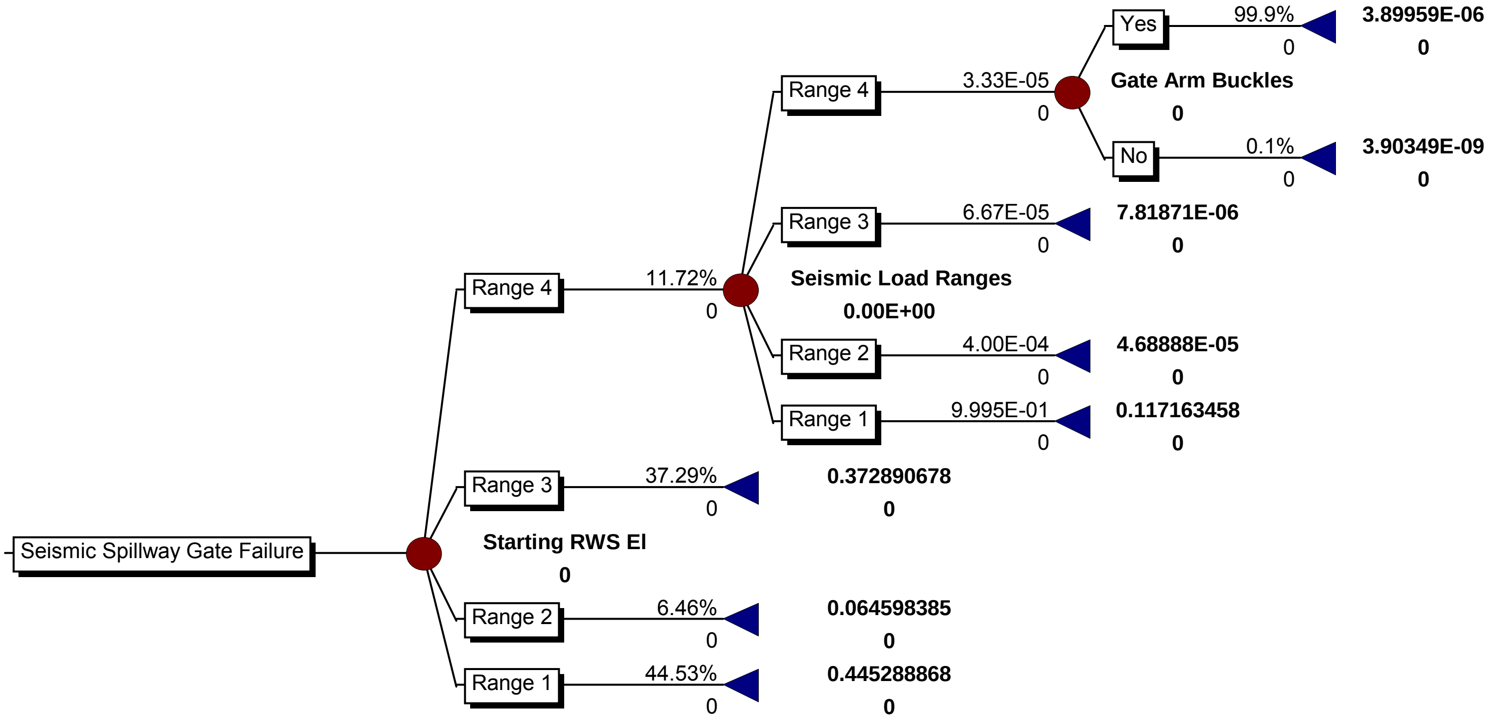


Figure 15-2 - Example Event Tree

Gate Analyses

Gate analyses are needed to evaluate the stresses in the gate members under combinations of reservoir and seismic loadings. A finite element model of the spillway gate is typically created, in which all members are modeled and evaluated under a variety of reservoir and seismic loading conditions. The key parameter to evaluate in the gate arms is the combined stress ratio, which is a parameter that reflects the combined axial and bending stresses in steel members. If the combined stress ratio is high in a gate arm, there is the potential for buckling of that arm.

It should be noted that radial gates typically include bracing to reduce the unsupported length (and hence buckling potential) of the gate arms. The finite element analysis may indicate that a bracing member is the critically stressed component, and a judgment will be needed as to whether the bracing would fail, perhaps leading to a greater unsupported length and combined stress ratio for the gate arms.

Hydrodynamic interaction must be included in the gate analyses. This is typically done using Westergaard's added mass, which is excited by a seismic coefficient related to the peak horizontal accelerations and applied to the gate as a load. The horizontal dimension of the added water, b, is a function of the depth below the reservoir surface, y, and the total reservoir depth, h, or $b = 7/8\ (hy)^{0.5}$. An important consideration is what total depth of water, h, to use in calculating the mass for gates atop a concrete dam, as shown in Figure 15-3. Experience with incompressible fluid element analysis on dams approximately 200 feet high suggests that if the gates are inset from the face of the dam, the mass can be taken as approximately the average of that using h as the full reservoir depth and h as the depth to the gate sill.

The acceleration used to excite the water mass must include any amplification that occurs as a result of the response of the structure. Typically, a reduction is taken of the peak ground acceleration – usually a factor of 0.85 is applied. This adjustment recognizes that the peak acceleration most likely represents a single loading spike and is less representative of the overall load imposed by the earthquake.

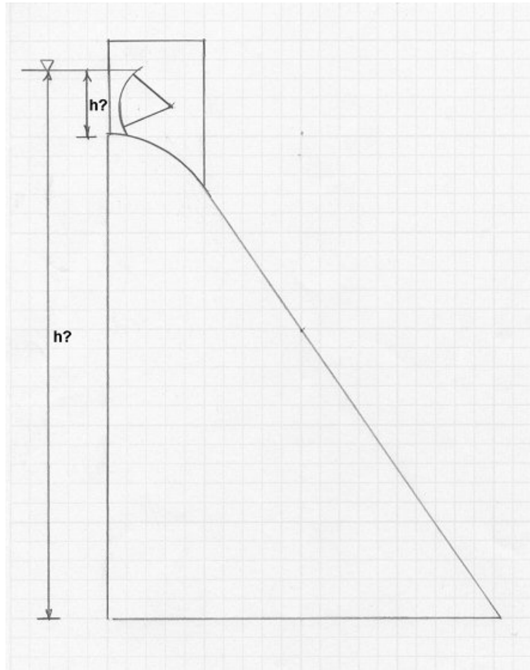


Figure 15-3 – "h" in Westergaard's Added Mass Equation

For radial gate arm buckling, the combined stresses are the axial compressive stresses and the vertical and horizontal bending stresses which act at the extreme fibers at the same cross section of the arms wide flange (or other) beam. The combined stresses were developed and presented by AISC (American Institute for Steel Construction; 1989) in equation H1-1 as shown below.

The equation is the sum of three ratios and all three components represent stress ratios at the same location along the gate member. The numerator of each ratio is the actual stress, and the denominator represents the allowable stress with its associated factor of safety. The first term is the axial compressive stress, the second term is the bending stress about the strong axis of the cross section, and the third term is the bending stress about the weak axis. For transition loadings, such as wind, seismic, or friction when operating a radial gate, the AISC code allows a one third increase in the stresses. That is, the allowable combined stresses (the sum of the three ratios) is less than or equal to 1.3. Evaluating the individual variables given in the combined stress equation is complicated, and requires background of other chapters with the AISC Specification for Structural Steel Buildings.

The simplest term and ratio to evaluate is first term – the axial compressive stress. A preliminary (simplified) arm buckling failure analysis would start with calculating the stress level for this axial stress term. It generally represents the largest contributor to the combined stress. If its value (ratio) is 0.8 or greater than a judgment whether a more refined (e.g. a 3D structural computer analysis) should be made. The pin frictional moment may be considered a transient moment acting on the arm sections in the vertical plane near the trunnion hub. Depending on the orientation of the arm’s wide flange beam (or other), it would contribute to the bending stress of the second or third term).

$$\frac{f_a}{F_a} + \frac{C_{mx}\, f_{bx}}{(1 - \frac{f_a}{F'_{ex}})F_{bx}} + \frac{C_{my}\, f_{by}}{(1 - \frac{f_a}{F'_{ey}})F_{by}} \leq 1.0$$

Combined Stress Ratios; AISC Eqn. H1-1 (1989)

If the initial analysis indicates a potential issue with spillway radial gates, complex 3-D finite element studies that models the reservoir along with the gate members could be considered to examine strain rate effects, but extreme care is needed to test and verify the model. A critical check that is needed to develop confidence in the model is to ensure that the reservoir does not separate from the gate and that the loading on the gate is as expected.

Reservoir Load Ranges

Reservoir load ranges are typically chosen to represent a reasonable breakdown of the larger reservoir range from the normal water surface (typically at or near the top of the gates in the closed position) and an elevation in the lower half of the gate in which stresses in the gate members are not a concern. The number of load ranges depends on the variation in failure probability, and should be chosen as much as possible to avoid large differences in failure probability at the top and bottom of the range. Historical reservoir elevation data can be used to generate the probability of the reservoir being within the chosen reservoir ranges, as described in the sections on Reservoir Level Exceedance Curves and Event Trees.

Seismic Load Ranges

Seismic load ranges are typically chosen to provide a reasonable breakdown of the earthquake loads, again taking into account the variation in failure probability to avoid large differences between the top and bottom of each range. The total range should include loading from the threshold level (load at which AISC code value designs are exceeded) at the lower end, to the level at which failure is nearly certain, or to the level at which the load probability multiplied by the maximum gate failure consequences is still below Reclamation Public Protection guidelines (the latter of which assumes a conditional gate failure probability of 1.0). Seismic hazard curves are used to generate the probability distributions for the seismic load ranges, as described in the sections on Seismic Hazard Analysis and Event Trees.

Conditional Failure Probabilities

The results of a finite element gate analysis can be used to estimate failure probabilities under a given set of loading conditions. The following fragility curve (Table 15-1) relates the combined stress ratio to the probability of a buckling failure, based largely on the judgments of those familiar with the AISC structural steel "code" and the safety factors implicit in that code. The combined stress ratio formula incorporates safety factors. The safety factors have been accounted for in the fragility curve and should not be removed when calculating combined stress ratios. For seismic conditions, the AISC code allows a combined stress ratio of 1.3. Because this is a code design, which incorporates a number of safety factors, the probability of failure is estimated to be very low, or about 0.001 for this condition. When the combined stress ratio reaches about 1.8, the steel gate arms should be close to their ultimate buckling capacity. For this reason this combined stress level was assigned a failure probability of 0.9. Fragility curve values for combined stress ratios other than the anchor point values were determined by gradually transitioning the values between the anchor points and establishing failure probabilities of 0.99 and 0.999 at combined stress ratios of 2.0 and 2.5 respectively.

Table 15-1 - Gate Failure Fragility Curve

Combined Stress Ratio	Probability of Failure (1 gate)
< 1.0	0
1.0 to 1.3	0.001
1.3 to 1.4	0.001 to 0.01
1.4 to 1.6	0.01 to 0.3
1.6 to 1.8	0.3 to 0.9
1.8 to 2.0	0.9 to 0.99
2.0 to 2.2	0.99 to 0.999
> 2.2	0.999

With the fragility curve as a guide, estimates can be made for the probability of a single gate failing under different combinations of reservoir loads and earthquake loads. These estimates are made based on the highest combined stress ratio for the gate arms from the structural analyses. Table 15-2 shows the combined stress ratios obtained for a number of gate analyses, with the corresponding estimated failure probabilities, and extrapolation of the results to load ranges where combined stress ratios were not calculated.

Table 15-2 – Single Gate Failure Probability

Res. El.	Acceleration at Trunnion Pin					
	0.25g	0.5g	0.75g	1.0g	1.5g	2.0g
466	4590 0.005	5650 0.05	0.5	8300 1.84 0.94	0.99	13800 3.0 0.999
462	0.001	0.01	0.3	0.5	0.8	0.999
458	3320 -	4200 0.001	0.005	6400 1.5 0.16	0.6	10200 2.5 0.999
454	-	-	0.001	0.05	0.5	0.99
450	2054 -	2530 -	-	3720 1.1 .001	0.3	6100 1.8 0.9
442	-	-	-	-	.001	0.3
434	600 -	760 -	-	1200 -	-	2000 .001

Gate load in kips
Combined stress ratio
Estimated failure probability of single gate

It should be noted that a higher combined stress ratio can be achieved for a lower total gate load, in some circumstances. This is the case in Table 15-2 for the 2.0g and El 450 combination and the 1.0g and El 458 combination, which is caused by a smaller total gate load being concentrated into the lower gate arms for the 2.0g and El. 450 load combination. .

Statistical Considerations for Multiple Gates

Spillways with multiple gates can have a variety of potential gate failure outcomes, ranging from one gate failing to all the gates failing. Pascal's triangle provides the number of combinations of each outcome for a given number of gates. Figure 15-4 shows the Pascal's triangle coefficients.

For a spillway that has six radial gates, the Pascal's triangle coefficients are highlighted in yellow. The coefficients represent the number of combinations of each outcome, as follows:

0 gates failing – 1 combination
1 gate failing – 6 combinations
2 gates failing – 15 combinations
3 gates failing – 20 combinations
4 gates failing – 15 combinations
5 gates failing – 6 combinations
6 gates failing – 1 combination

It can be noted that the triangle is constructed with “1’s” along the sides (representing the number of combinations of zero gates failing and of all gates failing). The number in each cell is then filled in by adding the two numbers diagonally above the cell. These numbers are used as coefficients in the probability equations. For example, Table 15-3 provides the equations for various failure outcomes (from zero to eight gates failing) based a spillway with eight gates (see far left column). The total at the bottom is the probability of one or more gates failing (i.e. is the sum of from 1 to 8 gates failing and does not include the probability of zero gates failing).

The generic form of the equation for a failure outcome (the outcome represents the number of gates that fail) is as follows:

$$P_v = C\left(\left(P_f\right)^y\right)\left(\left(1 - P_f\right)^{n-y}\right)$$

where: P_y = probability of failure outcome, where y represents the number of gates failing for a specific outcome.
C = coefficient from Pascal’s triangle representing the number of combinations of a given failure outcome.
P_f = probability of a single gate failure
n = the total number of spillway gates

The portion of the equation represented by $(P_f)^y$ accounts for all the gates that fail. The portion of the equation represented by $(1- P_f)^{n-y}$ accounts for all the gates that do not fail.

It should be noted that this approach assumes that the failure probability of each gate is independent of the failure probabilities of other gates. This is not necessarily the case. It holds true if there is an unknown defect that is unique to each gate which controls its failure probability. On the other hand, if it were known that one gate was near failing (not necessarily related to a unique defect), then this would affect the failure probabilities for the other gates. However, the Bernoulli triangle approach seems reasonable, in that if the failure probability of a single gate is small, the failure probability of multiple gates is also small; whereas, if the probability of a single gate is high, the failure probability of multiple gates is also high, as illustrated in Table 15-3. The most likely outcome (number of gates that will fail based on the probability estimate of a single gate failing) can be predicted by multiplying the total number of gates by the estimate of a single gate failing. From Table 15-3, for a single gate failure probability of 0.16, the most likely outcome is 8 x 0.16 = 1.28 or close to 1 gate failing. This is supported by the results in the table.

Typically, the combination of lower seismic load and lower reservoir elevation will have a significantly greater likelihood than higher seismic load and higher reservoir elevation, in each load range. Therefore, assigning equal weight to the boundary failure probabilities for a load range is generally conservative. This is especially true when there is a large range of failure probabilities at the boundaries of the load range (in which case it may be appropriate to look at smaller load ranges). Thus, the tree is often run using conditional failure probabilities that represent both the average of the ends of the ranges, and the lower ends of the ranges. If there is a large difference in the results, then additional refinement or weighting is probably needed (see also the section on Event Trees).

Table 15-3 – Example Pascal's Triangle Failure Probability Estimates

Probability for Single Gate → Failure		0.001	0.05	0.16	0.94
No. of Gates Failing	Equation for "x" Gates Failing	Probability for "x" Gates Failing	Probability for "x" Gates Failing	Probability for "x" Gates Failing	Probability for "x" Gates Failing
0	$1P^0(1-P)^8$	0.99	0.66	0.25	1.7E-10
1	$8P^1(1-P)^7$	0.0079	0.28	0.38	2.1E-08
2	$28P^2(1-P)^6$	2.8E-05	0.051	0.25	1.2E-06
3	$56P^3(1-P)^5$	5.6E-08	0.0054	0.096	3.6E-05
4	$70P^4(1-P)^4$	7.0E-11	0.00036	0.023	0.00071
5	$56P^5(1-P)^3$	5.6E-14	1.5E-05	0.0035	0.0089
6	$28P^6(1-P)^2$	2.8E-17	3.9E-07	0.00033	0.070
7	$8P^7(1-P)^1$	8.0E-21	5.9E-09	1.8E-05	0.31
8	$1P^8(1-P)^1$	1.0E-24	3.9E-11	4.3E-07	0.61
Total		0.0080	0.34	0.75	1.00

Number of Gates															
0	1														
1	1	1													
2	1	2	1												
3	1	3	3	1											
4	1	4	6	4	1										
5	1	5	10	10	5	1									
6	1	6	15	20	15	6	1								
7	1	7	21	35	35	21	7	1							
8	1	8	28	56	70	56	28	8	1						
9	1	9	36	84	126	126	84	36	9	1					
10	1	10	45	120	210	252	210	120	45	10	1				
11	1	11	55	165	330	462	462	330	165	55	11	1			
12	1	12	66	220	495	792	924	792	495	220	66	12	1		
13	1	13	78	286	715	1287	1716	1716	1287	715	286	78	13	1	
14	1	14	91	364	1001	2002	3003	3432	3003	2002	1001	364	91	14	1

Figure 15-4 – Pascal's Triangle for Multiple Gate Failure Probability Coefficients

Consequences

Consequences are a function of the number of gates that fail and the reservoir level at the time of failure (or the breach outflow). It is usually assumed that failure will result in a completely unrestricted spillway bay (the gate fails and washes away). This may not always be the case and the gate may not be completely removed, which could limit discharge for a failed gate to something less than that represented by a free-flow discharge (no restriction through bay). In this example at least 4 gates need to fail to exceed the safe channel capacity of 160,000 ft^3/s. However, smaller flows from fewer gate failures could impact recreationists adjacent to the river. Loss of life can be estimated from these breach flows and the estimated population at risk that would be exposed to the breach outflows using the procedures outlined in the section on Consequences of Dam Failure. To estimate a weighted loss of life for each seismic load and reservoir elevation range, the estimated loss of life associated with various gate failure outcomes (i.e. number of gates that fail) is multiplied by the conditional failure probability for the corresponding outcomes. The total (sum) conditional loss of life estimate is then divided by the total (sum) conditional failure probability estimate to arrive at the weighted average loss of life value. Example calculations for weighted loss of life are shown in Table 15-4, for a given reservoir elevation and single gate failure probability.

Table 15-4 – Weighted Average Loss of Life – Single Gate Failure Probability (P) = 0.16, RWS El 458

Number of Gates Failing	Probability of Failure Equations	Probability (P_x) of (x) Gates Failing	Expected Value Loss of Life	Loss of Life for (x) Gates Failing x (P_x)
1	$P_1 = 8(P)^1(1-P)^7$	0.38	8*	3.0
2	$P_2 = 28(P)^2(1-P)^6$	0.25	16*	4.0
3	$P_3 = 56(P)^3(1-P)^5$	0.096	23*	2.2
4	$P_4 = 70(P)^4(1-P)^4$	0.023	30*	0.69
5	$P_5 = 56(P)^5(1-P)^3$	0.0035	147	0.51
6	$P_6 = 28(P)^6(1-P)^2$	0.00033	164	0.054
7	$P_7 = 8(P)^7(1-P)^1$	1.8E-05	181	0.0033
8	$P_8 = 1(P)^8(1-P)^0$	4.3E-07	201	8.6E-05
Totals		0.75		10.5

* Loss of life due to recreational activity only

For this case, the Weighted Average Loss of Life = 10.51/0.75 = 14. The consequences for each seismic and reservoir load range are considered in the same way as the conditional failure probability. If the average of the load range boundaries produces risks that are considerably different than using the low value for the load range boundaries, additional refinement or weighting should be considered.

Results

The complete event tree for the example described here is shown in Table 15-5. Due to the large number of load ranges, it is usually easier to enter the event tree as rows and columns in a spreadsheet than to use Precision Tree. If Precision Tree is used, the resulting tree will take up several pages. It is important to review the results and isolate the major risk contributors. In this case, the risk is fairly evenly distributed between the seismic load ranges, with the lower load range contributing the least risk, and the middle load ranges contributing the most. The upper few reservoir ranges contribute the most risk.

Accounting for Uncertainty

The method of accounting for uncertainty in the seismic loading is described in the section on Event Trees. Typically, the reservoir elevation exceedence probabilities are taken directly from the historical reservoir operations data, which do not account for uncertainty. Uncertainty in the failure probability and consequences are accounted for by entering the estimates as distributions (as describe above) rather than single point values. A “Monte-Carlo” simulation is not practical for this failure mode, given the complexity of the calculations. Parametric studies should be considered however, to establish a reasonable range for the estimates.

Consequences of gate failure may also have uncertainty related to the breach outflow that will occur. While it is usually assumed that the gate is completely removed and that free-flow conditions exist, this may not always be the case. It may be appropriate to consider breach outflow based on a range of conditions – from free-flow conditions to restricted flow due to the gates partially blocking the spillway bay.

Table 15-5 – Event Tree Calculations

Seismic Load	Seismic Load Probability	Reservoir Elevation	Reservoir Probability	One or More Gates Fail	Annual Probability	Conseq	Annualized Life Loss
> 2.0g	2.00E-06	462 - 466	0.03	100.00%	6.00E-08	228	1.37E-05
	2.00E-06	458 - 462	0.04	100.00%	8.00E-08	212	1.69E-05
	2.00E-06	454 - 458	0.05	100.00%	1.00E-07	191	1.91E-05
	2.00E-06	450 - 454	0.03	100.00%	6.00E-08	164	9.84E-06
	2.00E-06	442 - 450	0.10	97.10%	1.94E-07	157	3.05E-05
	2.00E-06	434 - 442	0.12	47.50%	1.14E-07	7	7.98E-07
	2.00E-06	426 - 434	0.18	0.40%	1.44E-09	3	3.60E-09
Subtotal					6.10E-07		9.08E-05
1.5g - 2.0g	4.00E-06	462 - 466	0.03	100.00%	1.20E-07	220	2.63E-05
	4.00E-06	458 - 462	0.04	99.98%	1.60E-07	180	2.87E-05
	4.00E-06	454 - 458	0.05	99.88%	2.00E-07	138	2.76E-05
	4.00E-06	450 - 454	0.03	98.45%	1.18E-07	102	1.21E-05
	4.00E-06	442 - 450	0.10	72.30%	2.89E-07	44	1.27E-05
	4.00E-06	434 - 442	0.12	23.95%	1.15E-07	5	5.46E-07
	4.00E-06	426 - 434	0.18	0.20%	1.44E-09	1	1.80E-09
Subtotal					1.00E-06		1.08E-04
1.0g - 1.5g	1.50E-05	462 - 466	0.03	99.90%	4.50E-07	189	8.49E-05
	1.50E-05	458 - 462	0.04	93.68%	5.62E-07	105	5.89E-05
	1.50E-05	454 - 458	0.05	77.10%	5.78E-07	48	2.78E-05
	1.50E-05	450 - 454	0.03	57.08%	2.57E-07	23	5.97E-06
	1.50E-05	442 - 450	0.10	23.95%	3.59E-07	6	2.25E-06
	1.50E-05	434 - 442	0.12	0.20%	3.60E-09	1	4.50E-09
Subtotal					2.21E-06		1.80E-04
0.75g - 1.0g	3.40E-05	462 - 466	0.03	98.35%	1.00E-06	123	1.24E-04
	3.40E-05	458 - 462	0.04	75.68%	1.03E-06	45	4.58E-05
	3.40E-05	454 - 458	0.05	35.85%	6.09E-07	9	5.49E-06
	3.40E-05	450 - 454	0.03	8.83%	9.00E-08	5	4.28E-07
	3.40E-05	442 - 450	0.10	0.23%	7.65E-09	2	1.15E-08
Subtotal					2.74E-06		1.75E-04
0.5g - 0.75g	1.05E-04	462 - 466	0.03	58.80%	1.85E-06	45	8.38E-05
	1.05E-04	458 - 462	0.04	34.10%	1.43E-06	18	2.54E-05
	1.05E-04	454 - 458	0.05	8.83%	4.63E-07	6	2.66E-06
	1.05E-04	450 - 454	0.03	0.20%	6.30E-09	2	9.45E-09
Subtotal					3.75E-06		1.12E-04
0.25g - 0.5g	5.40E-04	462 - 466	0.03	46.10%	7.47E-06	10	7.47E-05
	5.40E-04	458 - 462	0.04	2.33%	5.02E-07	6	3.14E-06
	5.40E-04	454 - 458	0.05	0.20%	5.40E-08	2	1.08E-07
Subtotal					8.02E-06		7.79E-05
Total					**1.83E-05**		**7.44E-04**

What if Gate Failure Probabilities are not Independent?

As noted, the above evaluation assumes the failure probabilities for all gates are independent of each other. In reality, if a gate fails, it would make the potential failure of the remaining gates more suspect. It may be instructive to walk through a scenario such as that presented in Figure 15-5. In this example, each possible scenario related to potential failure of four gates is evaluated using an “updating” approach. Proceeding from left to right, the following scenarios are evaluated.

- Initially, the estimated probability of gate failure is 0.1. If gate number 1 survives a test, then there is more confidence that gate 2 will survive the test (say, failure probability is reduced to 0.05). Similarly, if gates 3 and 4 survive, additional confidence is gained, and the estimated failure probability reduces in each case.
- If gate number 1 fails the test, then confidence in the initial estimate becomes less. However, there still might be some confidence in the original estimate such that certain failure and the initial estimate are weighted equally at that point (failure probability = 0.55). If then gates 3 and 4 both fail the test, confidence in the original estimate is undermined, and a subsequently higher failure probability is concluded in each case.
- If gate 1 fails the test and gate 2 survives, or gate 1 survives and gate 2 fails, then perhaps the 50% failure rate, weighted equally with the original estimate, would be estimated for gate 3 (or 30% failure probability).
- If one of the first three gates fails the test, then the 1/3 failure rate might be averaged with the initial estimate of 0.1 to arrive at an estimated failure rate of 21.5% for gate 4. If two of the first three gates fail the test, then perhaps the 2/3 failure rate would be averaged with the initial estimate.

Figure 15-5 shows the difference between the above assessment and Pascal’s Triangle assessment discussed previously. It can be seen that the chance of one or more gate failures is higher using Pascal’s Triangle, although the chance of 3 or 4 gates failing is actually less. If, in this case, the consequences were to become significantly more severe with 3 or 4 gate failures, it may be important to take this into account in estimating the risks. Figure 15-6 shows another example of updating, this time with an initial estimated probability of gate failure of 0.5. The results are similar to those shown in Figure 15-5, with the total probability of failure being greater for the results using Pascal’s Triangle, but the chance of 4 gates failing actually being less for the updating approach.

Relevant Case Histories

Although radial gates have failed due to gate arm buckling as a result of trunnion pin friction (see the section on Trunnion Friction Radial Gate Failure), there are no known cases of radial gate failure as a result of earthquake loading.

Considerations for Comprehensive Facility Reviews

The complete analysis as described in this section is likely too time consuming to be performed during a Comprehensive Facility Review (CFR). Therefore, simplifications must be made. Fewer load ranges are typically evaluated, and only expected value estimates are entered into the event tree. Uncertainty is typically taken as plus or minus an order of magnitude. Average weighting schemes are typically used for results at the load range boundaries resulting in conservative risk estimates. If results of finite element gate analyses are available, they can be used to help define the load and reservoir ranges to be considered. If no gate analyses are available, searching for results related to similar gates should be undertaken.

Exercise

Consider a spillway with two radial gates, each 34.5 feet high by 51 feet wide. The outflow through one gate with the reservoir at the top of the gate (when closed; the reservoir is at or above this elevation 10 percent of the time) is 37,500 ft^3/s. The flow through one gate with the reservoir 20 feet up on the gate (the reservoir is at or above this elevation 90 percent of the time) is about 16,500 ft^3/s. Finite element analyses of a gate have been done with the reservoir at both of these elevations, and for peak horizontal ground accelerations of 0.2g (expected value annual exceedance probability = 0.001), and 0.5g (expected value annual exceedance probability = 0.0001) at the trunnion pin. The combined stress ratios for the most highly stressed gate arm are listed in Table 15-6.

Table 15-6 – Combined Stress Ratios

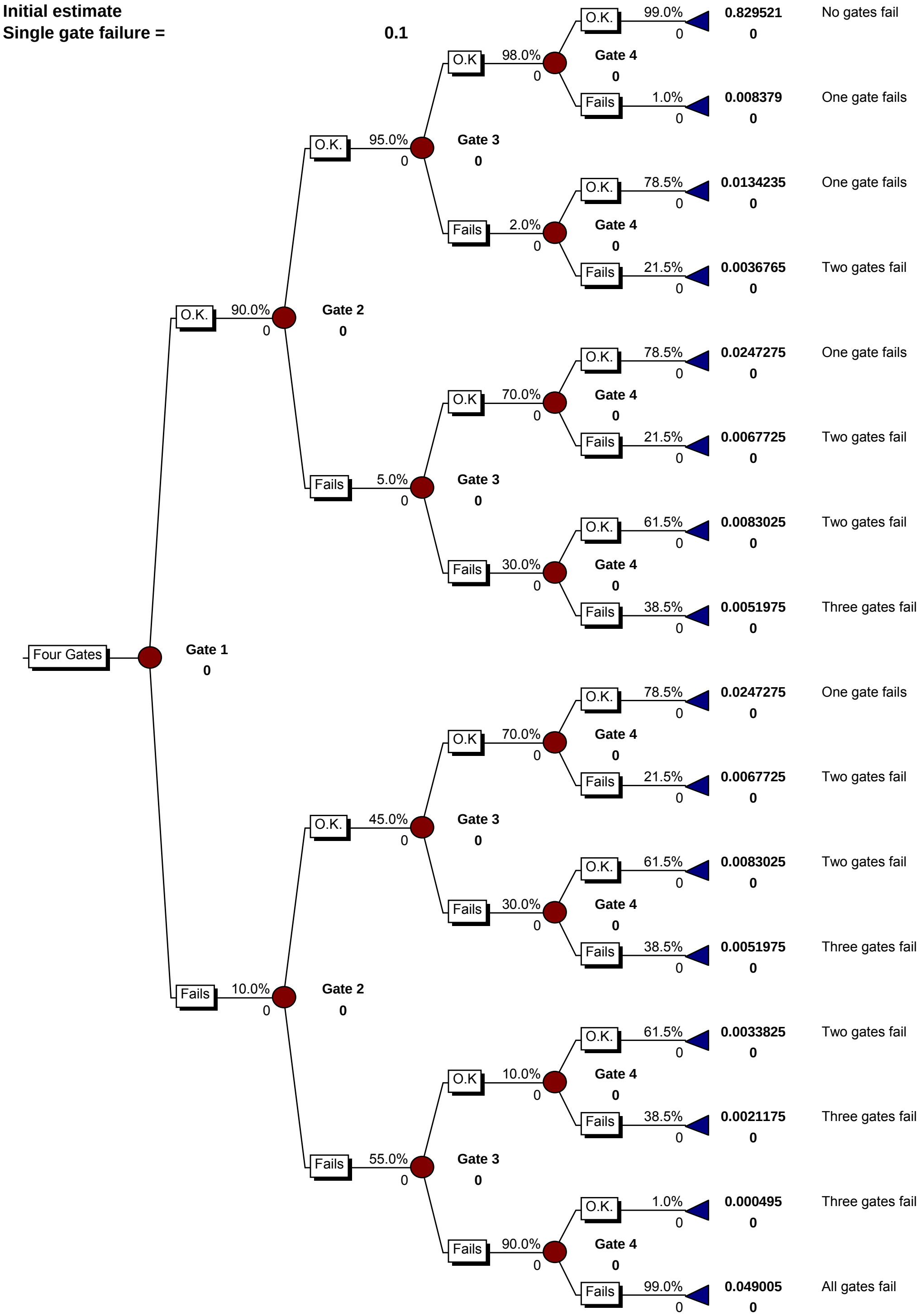
	0.2g	0.5g
Reservoir at top of gates	1.4	2.0
Reservoir 20’ up on gates	1.0	1.3

Estimate the expected value annual failure probability for one or more gates failing due to seismic loading.

References

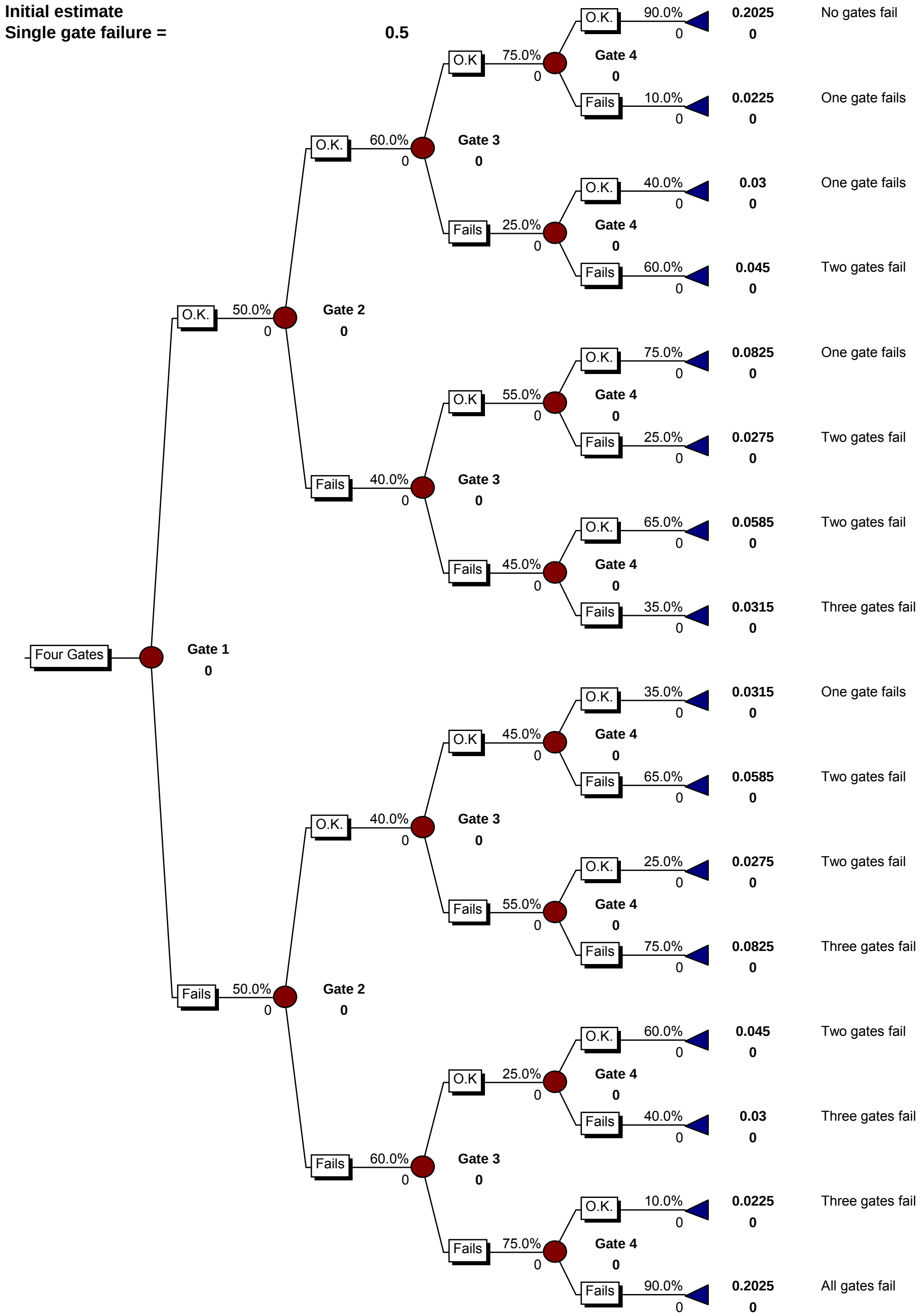
American Institute of Steel Construction, (AISC) Specification for Structural Steel Buildings, Allowable Stress Design and Plastic Design, Thirteenth Edition, Chapter H, Combined Stresses, June 1, 1989.

Initial estimate
Single gate failure = **0.1**



Pascal's Triangle			Tree	
No gates fail	$1{*}P^{0}{*}(1-P)^{4}$ =	0.6561	No gates fail =	0.8295
One gate fails	$4{*}P^{1}{*}(1-P)^{3}$ =	0.2916	One gate fails =	0.0713
Two gates fail	$6{*}P^{2}{*}(1-P)^{2}$ =	0.0486	Two gates fail =	0.0372
Three gates fail	$4{*}P^{3}{*}(1-P)^{1}$ =	0.0036	Three gates fail =	0.0130
Four gates fail	$1{*}P^{4}{*}(1-P)^{0}$ =	0.0001	Four gates fail =	0.0490
One or more		0.3439	One or more =	0.1705

Figure 15-5 – "Updating" Event Tree for Four Radial Gates



Pascal's Triangle			Tree	
No gates fail	$1*P^0*(1-P)^4$ =	0.0625	No gates fail =	0.2025
One gate fails	$4*P^1*(1-P)^3$ =	0.25	One gate fails =	0.1665
Two gates fail	$6*P^2*(1-P)^2$ =	0.375	Two gates fail =	0.2620
Three gates fail	$4*P^3*(1-P)^1$ =	0.25	Three gates fail =	0.1665
Four gates fail	$1*P^4*(1-P)^0$ =	0.0625	Four gates fail =	0.2025
One or more		0.9375	One or more =	0.7975

Figure 15-6 – "Updating" Event Tree for Four Radial Gates